arXiv:hep-ex/0003015v1 13 Mar 2000

PRESENT SITUATION OF DIFFRACTED X-RAY RADIATION AND RESONANCE (COHERENT) TRANSITION RADIATION INDUCED BY HIGH ENERGY CHARGED PARTICLES IN FREQUENCIES REGION EXIDING ATOMIC ONE.

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Abstract

The review is devoted to the modern investigations of electromagnetic radiation by relativistic charged particles propagating with constant velocity through the periodic media. Two examples of radiation are considered in this review, the first corresponds to the Bragg scattering of charged particles pseudophotons in crystals, the second one to the Fresnel scattering of pseudophotons in periodic medium. Both examples play essential role in construction new compact tunable sources in X-ray region.

1. Introduction

High-energy electromagnetic processes in medium have been summarized in my monograph in 1969 year and translated into English in 1972 [1]. (The numbering of chapters, paragraphs, formulas and total text of English edition are the same as in Russian version.) Since that time this field of high-energy physics developed catastrophically fast in many various directions, including quantum chromodynanic (see [2] and references therein). During that period of time many original publications, review articles and books have been published. The number of original publications is impossible to estimate. Only the physicists from former Soviet Union published in Physics Usphekhi since 1972 ten reviews and eleven monographs in various publishing houses. Numerous conferences, workshops and seminars in different countries were devoted to these problems. For example: traditional conferences in Russia (Tomsk, RREPS1993-1995-1997-1999), (see [3] and references therein), in Germany [4] (Tabarz, 1998) etc.

All these problems of high-energy radiation physics are based on the following underlying idea; the length of trajectory (coherence length) along the trajectory of initiating reaction particle increases with energy of incoming particle and the directionality of process (see Appendix). The history of this concept has been published in Russian by E.L. Feinberg. in his well known paper in Priroda [5], (see translation of [5] into English in Appendix). Among numerous problems from this field I will review in this paper only two; the diffracted X radiation (DXR) and the resonance transition radiation (RTR).

2. Diffracted X Radiation (DXR)

DXR has been considered in 1969 and included in Chapt.5 of book [1]. The theoretical consideration can be very simplified, if we follow the corresponding theory of X-ray scattering in crystals. Expanding electrical field of fast moving particle in time and variable part of dielectric susceptibility $\varepsilon_1(r)$ over vectors $\vec{g}$ of the reciprocal lattice.

$$\varepsilon = \varepsilon_0 + \varepsilon_1(\vec{r}); \quad \varepsilon_1(\vec{r}) = \sum n_{\vec{b}} \exp(i\vec{g}\vec{r}) \tag{1}$$

and using the theory of X ray scattering we get the following expression for scattered electric field at a distance R_0

$$\vec{E}'_\omega(\vec{R}_0) = \frac{e}{\varepsilon_0 R_0} \sum_{\vec{b}} n_{\vec{b}} \left[\vec{k}' \times \vec{k}' \times \left(\frac{\omega\vec{v}}{c^2} + \frac{\vec{g}}{\varepsilon}\right)\right] \cdot \frac{\delta[\omega - (\vec{k}' - \vec{g})\vec{v}]}{(\vec{k}' - \vec{g})^2 - (\omega^2/c^2)\varepsilon_0}. \tag{2}$$

Polarization of D.X.R. is linear and is given by expression (2). The radiation angle is determined, assuming the argument of the δ-function in (2) to be equal to zero

$$\cos\theta = \frac{c}{v\sqrt{\varepsilon_0}} + \frac{(\vec{g}\vec{v})c}{\omega v\sqrt{\varepsilon_0}} \tag{3}$$

where θ is the angle between velocity and scattered photon. Expression (3) often used in practice, for measuring the dependence of emitted photon energy upon the scattering angle θ. The equality (3) follows from energy-momentum conservation laws for photon radiation in a crystal if we take into account, that crystal can receive momentum inverse proportional to the length of periodicity.

Intensity is given by following expressions

$$d\vec{I}_{\omega,\vec{n}} = c\sqrt{\varepsilon_0}|\vec{E}'_\omega|^2 R_0^2 d\omega d\Omega \tag{4}$$

$$d\vec{I}_{\omega,\vec{n}} = \frac{e^2\omega^2 T}{2\pi\varepsilon^{5/2}c}\sum_{\vec{b}} n_{\vec{b}}^2 \left|\vec{k'} \times \left(\frac{\omega\varepsilon}{c^2}\vec{v} + \vec{g}\right)\right|^2 \times \frac{\delta[\omega - (\vec{k'} - \vec{g})\vec{v}]}{[(\vec{k'} - \vec{g})^2 - (\varepsilon_0/c^2)\omega^2]^2} d\omega d\Omega \ . \qquad (5)$$

Formulae for polarization (2), angular distribution (3), and the radiated energy in frequency interval $d\omega$ (5) are the base of kinematical theory [1] and have been confirmed in numerous theoretical and experimental papers.

The first experimental investigations of DXR have been done in Tomsk, by group of A.P. Potylitsyn [6,7], the second in Yerevan [8], third in Kharkov [9]. DXR initiated by protons has been observed in [10]. In papers [11,12,13] was shown that kinematical theory [1] may be sufficient to explain modern experimental results on spectral and angular distributions of DXR, as well as absolute differential yield. In papers [14] quantum theory of DXR has been developed and has been shown, that for relativistic particles, if recoil due to the photon emission is small, the quantum expressions coincides with corresponding expressions presented in [1]. I will mention that like dynamical theory of X-ray scattering, the corresponding theory in DXR has been developed in series of publications and included in monographs [15,16]. This type of radiation is referred in literature under names quasi-cherencov, parametric and even polarization radiation. To simplify the terminology I will use for this type of radiation the name dynamical theory of DXR The name PXR often used in literature for both type of radiation is meaningless and doesn't correspond to the nature of radiation (I thank H.Nitta for this comment). During the last years new experimental investigation has been accomplished, which improved our knowledge of DXR. The remarkable features of DXR (monochromatic with continuously variable wavelength, propagation direction well separated from the electrons beam one, small energy and angular spread of the order of magnitude one over gamma, and at last the small sizes of setup) suggest that DXR can be an perspective X- ray source in future. A series of paper [17,18] has been published recently by joint group from Institute fuer Kernphysik in Darmstadt, from Kharkov, Rossendorf and Johannesburg, using superconducting linear accelerator S-DALLINAC with electron energy below 10 MeV. The line width of 8.98 keV DXR for electron energy 6 Mev has been measured applying an absorption technique using a copper foil and tuning the energy of the DXR peak across the K-absorption edge of copper. The spectral density in the peak deduced from experiment was, $I = 0.95 \times 10^{-7}$

photons/(electron sr.eV), and linewidth 48 eV (see Fig.1). In paper [19] upper limits of line width of DXR 1.2 eV and 3.5 eV have been determined for (111) and (022) reflections of silicon at photon energies of 4966 eV and 8332 eV. Investigations of the line width of DXR at the Mainz Microtron MMI a relative energy width ($\Delta E/E = 10^{-5}$ should be reached for the silicon (333) reflection [19,20]. The spectral and angular distribution of DXR have been studied mostly in silicon and diamond crystals over a range from a few MeV up to several GeV of electrons and are in consistent with the theory [1].

The last experiments carried out by physicists from Germany (Werner Heisenrberg Institute and Institute fuer Kernphysik), [21,22] has shown close to 100% linearly polarization at every single point of photons angular distribution, with agreement with the theory [1]. In these investigations polarization has been analyzed by means of novel method of polarimetry exploiting directional information of the photoeffect in a charge coupled device consisting of 1.3×10^6 square pixels of 6.8mkm [23]. The advent of such devices opens a promising route towards a universal X-ray detector for simultaneous imaging, spectroscopy and polarimetry. The angular distributions of DXR polarization directions, calculated recently [24] on the base of the theory [1], are close to the experimental and calculated data presented in [21,22] for DXR in forward and backward hemispheres, but in disagreement with calculations [21,22] for DXR polarization at right angle. The disagreement between calculations is due because in [21,22] the longitudinal density effect [25] has been neglected (private remark from A.V. Schagin). The discrepancy of both calculations with experiment [26] for polarization in forward hemisphere emission remains unsolved yet and new measurement is needed (private communication from R. Kottaus).

The physicist from Tomsk investigated influences of temperature on DXR intriducing Debay-Waller factor in expression (5). They obtained good agreement with experimental data [31]. In first publication devoted to the influence of acoustic waves and gradient of temperature on DXR shows that the intensity of DXR may be increased several times [32] (see Fig.2). Nevertheless intensity of DXR attained in laboratories in several keV domains is the same order of magnitude as synchrotron radiation of big accelerarators (see [3,4,33] and references therein).

Concluding this short review of DXR I will notice that more complicated theoretical and experimental problems remains unsolved. In particular the region of applicability of dynamical DXR theory and its correspondence with experiments [27,28,29] has not been investigated seriously. During the International Workshop on Radiation Physics, in Tabartz [4] Prof. Baryshevsky V. affirmed that dynamical version of DXR is necessary to understand experimental data [29]. On the other hand Prof. N. Nasonov maintains opposite statement.I. Feranchuk and A. Ivashin incorporated quantitatively electron multiple scattering and photon absorption in kinematics theory [30], but more subtle theoretical treatment is necessary.

3. Resonance Transition Radiation (RTR)

The well known expression for Transition Radiation (TR) introduced in physics in 1946 by V. Ginzburg and I. Frank received a new development, when it was investigated in radiation frequencies exceeding optical [34,35]. At that time the longitudinal density effect [25] and coherence length concept introduced in high-energy radiation processes in papers [36] were well known and the results of papers [34,35] can be easily understood [37] and derived from [25]. The problems arise when the expression for transition radiation, which is valid only for one interface, tried applying for many periodically spaced interfaces and in limiting case for periodic medium. It must be taken into account, that nonrelativistic charged particles propagating through periodic medium will emit photons with frequencies proportional to the frequency of propagation the periodicity of medium (resonance condition). For relativistic particles because of Lorenz transformation we get the following resonance condition

$$\cos\theta = \frac{c}{v\sqrt{\varepsilon_0}} - \frac{2\pi r c}{l\omega\sqrt{\varepsilon_0}}\cos\psi \tag{6}$$

where (ω-frequency of radiation, v -velocity of particle, (ε_0 - effective dielectric susceptibility, (θ - angle between incoming particle velocity and direction of radiation, (ψ - angle of incidence of charged particle onto the one-dimensional periodic medium, l-period of medium, r - number of emitting harmonic. The resonance condition (6) can be easily

derived using the energy-momentum conservation laws in periodic medium. This kind of TR was termed as RTR. For $l \rightarrow \propto$ we get the well-known Tamm-Frank expression for Vavilov-Cherenkov radiation in homogeneous medium. RTR consist of overlapping radiated harmonics, each has its threshold in energy of radiating particle and depends on parameters of medium. Theory of RTR has been published in my article presented for publication by L. Landau to Dokladi Acad. Nauk in 1960 [38] and published in Nuclear Physics in 1961 [39]. For periodic medium radiation on r-harmonic appears when the particle velocity exceeds the group velocity of corresponding photons.[1]

The most convenient medium for experimental investigation is laminar periodic medium with many plates (Fig.3). For laminar medium consisted with two different plats $\sqrt{\varepsilon}_0$ has simple form

$$\sqrt{\varepsilon}_0 = \frac{l_1\sqrt{\varepsilon_1} + l_2\sqrt{\varepsilon_2}}{l} \tag{7}$$

where l_1 and l_2 are thickness, $l = l_1 + l_2$ and ε_1 and ε_2 are dielectric susceptibilities of plates. For frequencies much more higher optical frequencies from inequality $|\cos\theta| \leq 1$, for each harmonic we get

$$\omega_{max} = \frac{4\pi cr}{l}\left(\frac{E}{mc^2}\right)^2 \geq \omega \geq \frac{l\omega_0^2}{4\pi cr} = \omega_{min} \ , \tag{8}$$

where ω_0 is the plasma frequency

$$\omega_0^2 = \frac{4\pi NZe^2}{m_e} \tag{9}$$

and for laminar medium

$$NZ = (N_1Z_1l_1 + N_2Z_2l_2)/l \tag{10}$$

From (8) we get the threshold energy for radiation harmonic of r-number. The intensity of RTR is given by following expression (see formula (28.92*) from [1] or paper [39]).

$$dI_{\omega,\theta} = \frac{e^2\theta^3 d\theta d\omega}{2\pi c}\left|\frac{\varepsilon_2 - \varepsilon_1}{\left(1 - \frac{v}{c}\sqrt{\varepsilon_1}\cos\theta\right)\left(1 - \frac{v}{c}\sqrt{\varepsilon_2}\cos\theta\right)}\right|^2 \times$$

[1]Beginning from I. Frank proposal, many physicists tried to increase the TR intensity from one interface using many foils. The calculations in optical region were cumbersome and negaive, because of neglecting resonance condition. This problem was similar to the corresponding one in saturation problem of ionization losses solved by E. Fermi, who enlarged the I. Tamm calculation for Cherenkov-Vavilov radiation.

$$\times \sin^2 \left[\frac{l_1 \omega}{2c} \left(1 - \frac{v}{c} \sqrt{\varepsilon_1} \cos\theta \right) \right] \frac{\sin^2 \frac{n\beta}{2}}{\sin^2 \beta} \ . \tag{11}$$

where the first term corresponds to Ginzburg-Frank transition radiation, the second corresponds to the interference of radiation from two interfaces of one plate and the last term corresponds to the coherent summation of radiation from n-plates. The quantity β equals

$$\beta = \left(1 - \frac{v}{c} \sqrt{\varepsilon_1} \cos\theta \right) \frac{\omega l_1}{2v} + \left(1 - \frac{v}{c} \sqrt{\varepsilon_2} \cos\theta \right) \frac{\omega l_2}{2v} \tag{12}$$

If the number of plates increases the last term can be substituted by delta function and we get the resonance condition (6). The theory of RTR depends dramatically on coherence length, if for example coherence length exceeds the distances between two interfaces in a plate the radiation from two interfaces must be summed coherently. The same result takes place for total periodic medium. Radiation from plates will sum independently if the distances between plates exceed the coherence length. We shall discuss the related experiments later. The RTR including absorption influence and multiple scattering effects has been discussed in [39,1]. But in that time (sixteenths years) we were interested to apply RTR for construction a new type of counters for very high energies of particles were Cherencov detectors were insensitive. These new detectors has been constructed by group of F.R. Arutunian in 1963 [40,41]. In following investigations the property of these detectors were improved and reviewed in many publications [42,43,44,45]. They are used now for identification of particles in modern high-energy accelerators (see for example [46] and references therein).

Since 1985 RTR received a new impact for developing in different domain of physics. Joint group of physicist from Stanford University and Livermore Lawrence Laboratory investigated RTR using the linear accelerator with energy of electrons equal to 17.2, 25, 54 MeV to produce photons in keV region [47]. Stack of Be, C, Al foils consistent each from18 foils with thickness 1 μm separated in distance 0.75mm (for carbon) and 1.5mm (Be and Al) have been used. Experimental data for RTR intensity angular and spectral distributions presented in [47] confirms the theory of interference at the interfaces of a single foil. The authors assert that an easy-to-tune source of intense polarized monochromatic radiation holds much promise for submicron lithography. For instance, a 0.5 μm

resolution was reported in [48]. Though in [47-49] no interference effects were observed with radiation from different beryllium foils (see Fig.4), the same authors noticed an unusual interference pattern in [50]. Interesting observations of interference effects in RTR were made by French researchers [51] at the electron accelerator in Sacle (see Fig.5). The achievement of 0.3 μm resolution was reported in [52]. In the soft range of the spectrum (1-3 keV) the RTR spatial distribution for electron energy of 50-228 MeV was observed in [53]. Here attention is drawn to the fact that RTR results through the whole radiator stack, which forms the periodic structure, and concentrates in the solid cone whose angle grows with electron energy. Changes in the periodic structure parameters (e.g. electron energy, structure size) suppress interference effects and give rise to TR for which the emission angle, in coincidence with the TR theory, is inversely proportional to the electron energy (see Fig.6). Teams from universities of Kyoto, Tohoku, Hyrosimo, Tokyo (I. Endo et al.) and Tomsk Institute for Nuclear Physics (A.P. Potylitsin et al.) in cooperation with various Japanese firms have made a lot of research into RTR at accelerators in Japan [54-58]. The goal of the research was not only to investigate resonance effects in RTR but also to determine the parameters of the electron beam and active medium best suitable for practical implementations of RTR.

4. The radiation of moving particles on complex structures (DXR+ RTR)

The use of complex periodic structures was first suggested in the 90s when it became clear that the development of effective kiloelectron-volt generators requires increased intensities of DXR+ RTR [59]. Russian and Japanese physicists joined efforts to conduct research in this area. Papers [60] present the results of the irradiation of a target consisted of three crystals 16 (m thick with 800-MeV electrons (the synchrotron in Tomsk (Fig.7a)) and with 900-MeV electrons (the linear accelerator in Tokyo). Besides DXR, in the first crystal layer of the stack the electron beam generates RTR, which undergoes Bragg diffraction on the following crystal layers. This gives rise to the effective growth of emission (a 1.7-times increase was observed in the experiment). It should be noted that with the emission angle of the same order the RTR intensity and spectral width is much greater than that of DXR. The difference is that RTR follows the electron path, while

DXR propagates along Bragg's angles of refraction from the corresponding crystal planes in the reciprocal lattice. The authors introduced a new name for this type of emission - parametric (diffracted) RTR (substituting letter P by D (DRTR)), which we will further keep to. The next experiment [61] dealt with a 900-MeV electron beam and a target consisted of ten mylar foils and graphite crystal (Fig. 7b). The authors assert that even with a few foils DRTR follows Bragg's angles and is much more intensive than DXR. The last joint works of these authors [62,63] investigates radiation in the keV spectral range in a periodic medium consisting with crystalline plates. A 900 MeV electron beam and a target of 1 to 100 plates of monocrystal silicon were used in the experiment (see Fig.7c). The DRTR intensity of 35.5 keV photons proved to be comparable to that of synchrotron emission caused by a 1.7 GeV electron beam. The paper also considers the relationship between the radiation intensity and the number of plates - the issue that was discussed earlier in [57]. Papers [62], [63] and [4] (the last citation refers related papers presented at the meeting in Tabarz, Germany, 1998) build a theory that establishes a link between RTR and diffraction radiation that caused by a charged particle flying over a surface with periodic irregularities. In the experiment an electron beam propagated over a GaAs plate whose surface had 300 identical strips which were 10 μm wide, 100 μm high and spaced 33 μm apart. The authors observed radiation that consisted of DXR and DRTR, the intensity of the latter being much higher.

A great deal of theoretical papers discussing interference of various kinds of radiation has been published recently. Paper [64] offers a method of separating DXR and DRTR. Paper [65] shows that DXR output in mosaic crystal is the same as in a perfect crystal, and DRTR output is much higher. Diffraction of TR on a crystal structure is considered theoretically in [66]. Several relevant theoretical papers were also presented at the recent international conferences [3,4].

5. Conclusion

As I have already noted in Introduction, I have elucidated, out of a large set of questions, only DXR and RTR, which are developed recently in the numerous physical community. I hope to focus on other problems of yigh energy electromagnetic processes in

medium in my forthcoming reviews. Aouthor will be very grateful for any comments and suggestions to improve this review.

6. Acknowledgments

I am very grateful to Organizing Committee of RREPS'99 for the invitation to take part in the traditional symposium on the lake Baikal organized by Tomsk Nuclear Physics Institute. I would like to express a special gratitude to A.P. Potylitsyn, Yu. L. Pivovarov and L. Puzyrevich whose hospitality is very hard to overestimate. The work was performed within the program of the Ministry of Education and Science of the Republic of Armenia, grant $\#96-772$ and the INTAS grant $\#99-392$.

APPENDIX

EFFECT CONFIRMED 40 YEARS LATER.

"Nature", Russian Academy of Sciences, 1994, N1, pp. 30-33

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It was recently reported that in the accelerator center of Stanford University (SLAC) direct experimental evidence was obtained of the suppression of bremsstrahlung of relativistic particles in an medium [1], theoretically developed by L.D. Landau and I.Ya. Pomeranchuk 40 years ago [2]. This experiment confirms already the third of the important effects predicted in a series of works of Soviet theoreticians in 1952-1954. All these effects are bound by a common physical idea (or a basis), although they are displayed in different interactions of high-energy particles, and not only electromagnetic, but, as well, nuclear. This basis was built in 1952 in the Ph.D-thesis of M.L. Ter-Mikayelian [3], the post-graduate, of that time, in the Theoretical Department of the P.N. Lebedev Physical Institute, AS of USSR. The work was devoted to the investigation of the bremsstrahlung but not on single atom, as was studied before; it was considered in a medium, specifically, in a crystal.

The result of this work which seemed at that time paraamorphousdoxical, consisted in a statement that at very high energies, when the wavelength of either the emitted photon or the electron is tens of millions, milliards times shorter than the mean interatomic distance in the medium, the usual radiation pattern changes dramatically. Particularly, if the motion occurs along the crystal axis, this radiation may many times exceed on individual atoms. The process in this case is widely extended in space and includes a domain with characteristic sizes many times exceeding the interatomic separations. All atoms of the crystal in this domain act coherently, and as a result, the radiation is enhanced significantly. This length was, naturally, termed as the coherence length.

The work under discussion had forerunners. A possibility of the influence of crystalline structure on the bremsstrahlung of fast particles was discussed by B. Ferretti in 1950,

and still earlier, in 1935, by E.Williams, who developed independently the well-known, in theoretical physics, Weizsecker-Willians method. However, either the work of Ferretti or the notation of Williams (who obtained, by the way, an incorrect sign of the effect) remained unpersuasive and did not attract the attention until Ter-Mikayelian succeeded to show that the bases of the process are paradoxical (for that time) physical causes which turned out to have much wider significance than the explanation of radiation in crystals. This lead to the development of a new direction involving various processes in high-energy physics. Now attempts are made to apply these results to processes of of high-energy hadrons inside the nucleus regarded as a material medium.

Coherence length

Ter-Mikayelian succeeded to show [5] that in the processes at high energies where the particles are scattered at small angles (decreasing with the icrease of the energy), the longitudinal momentum, $q_{||}$, transferred to the target, drops, and, consequently, according to the uncertainty relation, $\Delta q_{||} \Delta x_{||} \geq \hbar$, the longitudinal distance $\Delta x_{||}$ involved in the process increases with the energy. Therefore, it is the coherence length, $L_{coh} \sim \hbar / q_{||}$, rather than the wavelength of the particle, that can be a measure of the size of domain, relevant for the effect. When speaking not especially of a crystal it would be reasonable to term this length otherwise, namelythe zone or length of process formation. In 1952 this looked incredible and even absurd since it was accepted that characteristic distances of formation of electromagnetic processes are of the same order as the wavelengths of particles involved (or the atomic sizes).

In order to illustrate this nontrivial result let us consider the process of bremsstrahlung of a photon with energy $\hbar\omega$ and momentum $\hbar\vec{k}$ on a fixed coulombian center. Let E_1 and $\vec{p_1}$ be the initial energy and momentum of the radiating relativistic particle of mass m while E_2 and $\vec{p_1}$ are the same quantities in its final state. Let us then use the energy and momentum conservation laws,

$$E_1 - E_2 = \hbar\omega \tag{1}$$

$$\vec{p_1} - \vec{p_2} - \hbar\vec{k} = \vec{q} \tag{2}$$

Where $\vec{q}$ is the momentum transferred to the nucleus, and project the latter on the initial

direction of particle's motion. For this purpose we multiply Eq. (2) by the initial velocity of the particle, $\vec{v_1}$:

$$\vec{v_1}\delta\vec{p} - \hbar\vec{k}\vec{v_1} = \vec{v_1}\vec{q} \approx |\vec{v_1}|q_\parallel \ ,$$

Where $\delta\vec{p} = \vec{p_1} - \vec{p_2}$, and $q_\parallel$ is the longitudinal momentum transferred along the motion of the emitting particle.

Since $\vec{v}\delta\vec{p} = \delta E = E_1 - E_2 = \hbar\omega$, we have for small energy variation, $\hbar\omega \ll E$, of the initially ultrarelativistic particle ($|\vec{v_1}| \approx |\vec{v_2}| \approx c$ and $k = \omega/c$),

$$q_\parallel = \tfrac{\hbar\omega}{c}\left(1 - \tfrac{v}{c}\cos\theta\right). \tag{3}$$

Where θ is the angle between the emitted and the direction of motion, $\vec{v_1}$, of the emitting particle. As the radiation at high energies is known to be sharply directed, the obtained formula should be considered as small θ . For $\theta \ll \sqrt{1 - v^2/c^2}$

$$q_\parallel = \tfrac{\hbar\omega}{c}\left(1 - \tfrac{v}{c}\right). \tag{4}$$

As it was mentioned above, the coherence length (formation zone) along the path of the emitting particle amounts by the order of magnitude to

$$L_{coh} \approx \tfrac{\hbar}{q_\parallel} \approx \tfrac{c}{\omega(1-v/c)} \approx \tfrac{E^2}{m^2c^3\omega}. \tag{5}$$

With the time of passing the zone being equal to

$$t_{coh} \approx \tfrac{L_{coh}}{v} \approx \tfrac{E^2}{m^2c^4\omega}. \tag{6}$$

This means that at $v \to c$ the quantity L_{coh} may reach macroscopic values. (For large variations of energy of the emitting particle, L_{coh} is given by an expression like (5). Paradoxically of this result is up to now being emphasized in review articles [6], although the results raises no doubts. However, in 1952 it was not at once that one succeeded to convince even Landau and Pomeranchuk of the correctness of these arguments, of the presence of the formation zone increasing with energy, and so on [7]. Nevertheless, already in autumn 1952 Ter-Mikayelian reported at Landau's seminar the details of his thesis, with complete mutual understanding and approval. It should be added only that the described effect was completely, in all theoretically developed details, checked experimentally in a crystalline medium, ten years later. At present it is used, in particular, to obtain quasimonochromatic and polarized (γ-quanta from electron accelerators [8].

The importance of the arisen conception of the length of formation was at once es-

timated by Landau and Pomeranchuk, and they (and not only they) began to think to further theoretically develop this phenomenon.

Influence of multiple scattering on the bremsstrahlung in amorphous medium.

First Pomeranchuk noticed to Ter-Mikayelian that if all what he said about the coherence length in the crystal is correct, then in an amorphous medium as well, the traditional Bethe-Hilter formula for the bremsstrahlung on a single atom shuld have been changed, due to the absorption on a distance termed the radiation length, at $L_{rad} \leq L_{coh}$. This statement raised no objections of either Ter-Mikayelian or Landau who advised to evaluate this effect. Soon, however, after examining the problem, Landau came to the conclusion that the influence of multiple scattering will take place rather than the influence of absorption by the emitting particle. Rather soon Landau and Pomeranchuk evaluated this effect and acquainted Ter-Mikayelian with the manuscript of their joint article asking to tell his remarks. A discussion of this work took place, and the article was approved. It happened so that Landau and Pomeranchuk, starting with the formula (5), and explaining, that, in accordance with the formula (6), the time tcoh "does very sharply increase with the energy and, as a cosequence, those distances between electron and nucleus play a role which significantly exceed atomic sizes", did not, apparently, by a misunderstanding only, refer to the work of Ter-Mikayelian. But he would not think (felt shy?) to tell them that it had to be done [9]. This lead to such a moving of events that this story seems to be not only quite appropriate here but also instructive from the point of view of the scientific ethics.

In that time conditions of isolation of Soviet Science a publication of our works in foreign languages was strongly prohibited as "cringing to abroad". Nevertheless, Landau's name in a published, even in Russian, article, attracted the attention of the famous American physicist Dyson. Having, naturally, not known about the Ter-Mikayelian's work Dyson suspected that an interesting effect should exist in a crystal, and published (in coauthorship with G. Ueberall) a paper in an american journal presenting a result coinciding with that of Ter-Mikayelian (and refered, of course, not to him but to Landau).

Learning this Landau sent urgently the reprints of Ter-Mikayelian's works to Dyson, USA, showing that the work he published had already been done here. In a reply letter Dyson appraised highly the works of Ter-Mikayelian and recognized that he with Ueberall obtained the same physical results using, however, another calculation technique. Landau there and then acquinted the participants of the next seminar with the Dyson's letter.

Being elegant and clear physically the work of Landau and Pomeranchuk needed some mathematical improvements. This has been done by A.B. Migdal [10] who used a fine and original technique to complete the Landau-Pomeranchuk theory, from quantitative point of view, to a logically closed form, and obtained an expression for the bremsstrahlung in amorphous medium with allowance for the influence of multiple scattering. This expression used sometimes to be termed the Landau-Pomeranchuk-Migdal formula. Our physicists used this formula frequently to calculate the development of broad electromagnetic showers of cosmic rays. It is just this formula that was recently confirmed experimentally in Stanford.

Longitudinal density effect.

With these works the investigations of pecuiliarities of the radiation of ultrafast particles did not stop. Ter-Mikayelian generalized very soon the work of Landau-Pomeranchuk in he sense that he took into account the role of the dielectric polarization of the amorphous medium [11]. As it turned out, this polarizations affects the radiation of "soft" quanta with the energy of the order of or less than

$$\hbar\omega_{crit} = \hbar\omega_0/\sqrt{1 - v^2/c^2} \ . \tag{7}$$

Here $\omega_0^2 = 4\pi NZe^2/m$ is the squared plasma frequency, N the number of atoms per cm^3, m and e the electronic mass and charge, Z the number of electrons in the atom. The estimation of influence of the medium polarization on the formation length can readily be obtained from the above expressions by taking into account that in a medium we have actually $k = \frac{\omega}{c}\sqrt{\varepsilon}$, with ε being the dielectric constant of the medium. For the frequencies considerably exceeding the atomic ones:

$$\varepsilon = 1 - \omega_0^2/2\omega^2 \ .$$

Substituting correspondingly k in the expression (2), it is easy to see that the formula for

the coherence length takes the form

$$L_{coh} = \frac{c}{\omega}\left[1/\left(1-\frac{v}{c}+\frac{\omega_0^2}{2\omega^2}\right)\right].$$

This length is now "cut" for the photons at frequencies $\omega \leq \omega_{crit}$. In this case, the increase in the energy of the emitting particle ($v \to c$) results in that L_{coh} remains constant at a given frequency ω, which leads to an essential modification of either the Bethe-Hitler or the Landau-Pomeranchuk formula in the region of very soft quanta [12].

This density effect in the bremsstrahlung is in way similar to the density effect in ionization losses discovered by E. Fermi. The difference is following: in the second case it is the effective impact parameters (i.e. the distances in the direction perpendicular to paths of particles) that are "cut", while in the first case it is the longitudinal distances along the path of the emitting particle. In this connection the Stanford physicists term this phenomenon the longitudinal density effect with referring to the work [13] of Ter-Mikayelian. Unfortunately, in the experiment performed in Stanford University, the intensity of emitted photons was measured in dependence on their energy only in the region from 5 to 500 MeV. Since the electron energy was 25 GeV the frequencies of those photons exceeded, and the longitudinal density effect could not still be displayed to the full extent. It would be interesting to conduct corresponding experiments (even at considerably lower energies of the emitting particle) for the emission spectrum of photons at frequencies of the order of or less than (crit. In principle, this method could be employed for measurements of fast particle energies which is important for the experimental physics of ultrahigh energies.

Application to hadronic processes.

We have already mentioned that the increase of the formation zone with the energy of relativistic particles, revealed by Ter-Mikayelian, was applied also to high-energy hadronic processes. Here three consequent effects can be mentioned. The first, so to say, preliminary, is not of particular importance and has not been checked experimentally. It is valuable mainly from the methodological point of view. With use of this effect it turned to be possible to calculate the emission of photons by a charged pion the plane wave of which is incident no required to know the details of interaction between the pion and nucleus, it is sufficient that such a nucleus cuts a round hole in the plane wave. Then

a diffraction of pions occurs. And, as at small diffraction angles the length of zone of formation of emitted photon is very long, all needed integration can be made outside the nucleus and is performed without a detailed knowledge of the laws of interaction between the passing pion and nucleus [14]. However, the further attack in the same direction lead to much more important result.

A statement was made that a diffracted pion (like any hadron) can dissociate into other hadrons [15]. For example, a diffracted nucleon can emit a pion. Of course, in this case the probability of such a diffraction dissociation, i.e. of the process of pion emission by a diffracted hadron, can be calculated only by the perturbative theory giving merely a rough estimation of the cross-section of this process. But the cross-section is again determined by the integration over a large, increasing with the energy region outside the hadron or nucleus target. This gives the process some features, which allow distinguishing it among other hadron generation processes. Prediction of the diffraction dissociation of hadrons raised doubts for a long time, but already in sixties it was confirmed experimentally, and is now of great importance in high-energy hadron physics. It was very concretely described in "Regestic" as an exchange of pomeron, a quasiparticle with zero quantum numbers [16].

However, in that "preRegestic" age many unclear question arose concerning the nature of the effect which, as we saw, seemed to occur completely outside the nucleus-target. It was questioned: "Where enters the interaction with the nucleus?" Once Pomeranchuk answered with irritation: "Well, you can hold that a chaste conception occurred".

In order to clear the mechanism, a special work has been done concerning a similar possible effect, which is much more illustrative and calculable, that is the effect of diffraction splitting (dissociation) of a deuton [17]. It was then developed to a new direction-diffraction splitting of nuclei.

Introduction of the concept of coherence length, or formation zone, its use in various physical phenomena essentially changed our ideas about the radiation processes occurring at high energies. These are, we remind, in the first place, three effects that are under discussion here and confirmed experimentally: bremsstrahlung of photons in crys-

tal, diffraction dissociation of hadrons and the Landau-Pomeranchuk effect in amorphous media. It should be noted that related processes have been considered earlier as well, particularly, when V.L. Ginsburg and I.M. Frank predicted the existence of transition radiation. The use of concept of coherence length increasing with energy of emitting particle, in consideration of this phenomenon permitted to enrich its theoretical description, extend it considerably into the ultrahigh energy region, and then to create new detectors of relativistic particles [18].

All these works were done in a new years at the time when our country separated from the world science by an "iron curtain". When this curtain raised, the journal "Nuovo Cimento" ordered our scientists a number of reviews of soviet investigations on various problems. It was found that very much was done originally. As to the above-mentioned questions, reviews on these topics [19] contained already more than a dozen original; publications which resulted actually from the work of Ter-Mikayelian.

Footnotes

1. See,, e.g., CERN Courier, 1994, v. 34, N 1, p. 12-13.

2. L.D. Landau , I.Ya. Pomeranchuk , Dokl. AN SSSR 92, 735 (1953).

3. M.L. Ter-Mikayelian , JETP 25, 289 (1953); 25, 296 (1953).

4. I had a pleasure to be his supervisor.

5. See footnote [3].

6. A.I. Akhiezer , N.F. Shulga , Uspekhi Fiz. Nauk 137, 561 (1982).

7. A colourful discussion with them on this occasion I have described in my memoirs. See: E.L. Feinberg "Landau et al", Reminescence of L.D. Landau, Moscow, 1988, p. 253.

8.For details see: M.L. Ter-Mikayelian , "High Energy Electromagnetic Processes in Medium", N.Y., 1972.

9. Later this misunderstanding was corrested . See: V.B. Berestetskii , E.M. Lifshits , L.P. Pitaevskii, Quantum Electrodynamics, Moscow, 1980, p. 452.

10. A.B. Migdal , Dokl. AN SSSR 54, (1954); 105, 77 (1955).

11. M.L. Ter-Mikayelian , Dokl. AN SSSR 94, 1033 (1954).

12. By treating this effect the same technique was used as in the work of Landau and

Pomeranchuk. Migdal in his final publication of 1955 (see footnote [10]) introduced also the corresponding changes into his expressions.

13. See Landau , I.Ya. Pomeranchuk , JETP 24, 505 (1953).

15. Pomeranchuk I.Ya, Feinberg E.L., Dokl. AN SSSR 93, 439 (1953).

16. See: P. Lanshof , Pomeron, Priroda, 1994, N 12, p. 17-25.

17. This phenomenon was predicted independently and practically at the same time by different authors. See: A.I. Akhiezer , A.G. Sitenko , JETP 32, 794 (1957); E.L. Feinberg, JETP 29 115 (1955); R. Clauber , Phys. Rev., 88, 30 (19550.

18. See footnote [8]. For the relation between the transition radiation and the bremsstrahlung of ultrasort particles, see: M.L. Ter-Mikayelian, "Radiation of Particles in Periodic Media", Priroda, N 12, p. 68-73.

19. E.L. Feinberg , I.Ya Pomeranchuk , Nouvo Cimento, Supplemento, 111 652 (1956); E.L. Feinberg , Usp. Fiz. Nauk, 58 193 (1956).

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Figure captions

Fig.1. DXR spectrum at$\Theta = 42.9$ the 6.8 MeV electron beam direction.

Fig.2. The spectra of electrons emission in quartz crystal under acoustic waves ($\Box$) and unaffected ($\bullet$).

Fig.3. Particle passage through a stack of foils.

Fig.4. TR angular distribution in a plate. Thickness of beryllium foil was 1 μm. Experiment demonstrates interference effect in a plate.

Fig.5. Integrated from 1 to 10 keV TR and RTR angular distribution from TR (incoherent) (l_2=1.5 mm) and RTR (coherent) (l_2=115, 230 and 345 μm) stacks of 8 myler foils ($l_1 = 3.8 \mu m$).

FIg.6. i) The measured and calculated peak angle for TR (incoherent) and RTR (coherent); ii) The measured and iii) calculated spatial distribution for the (a) RTR, coherent and (b) TR, incoherent in myler stack.

Fig.7. Experimental setups (Japan-Russian joint project).

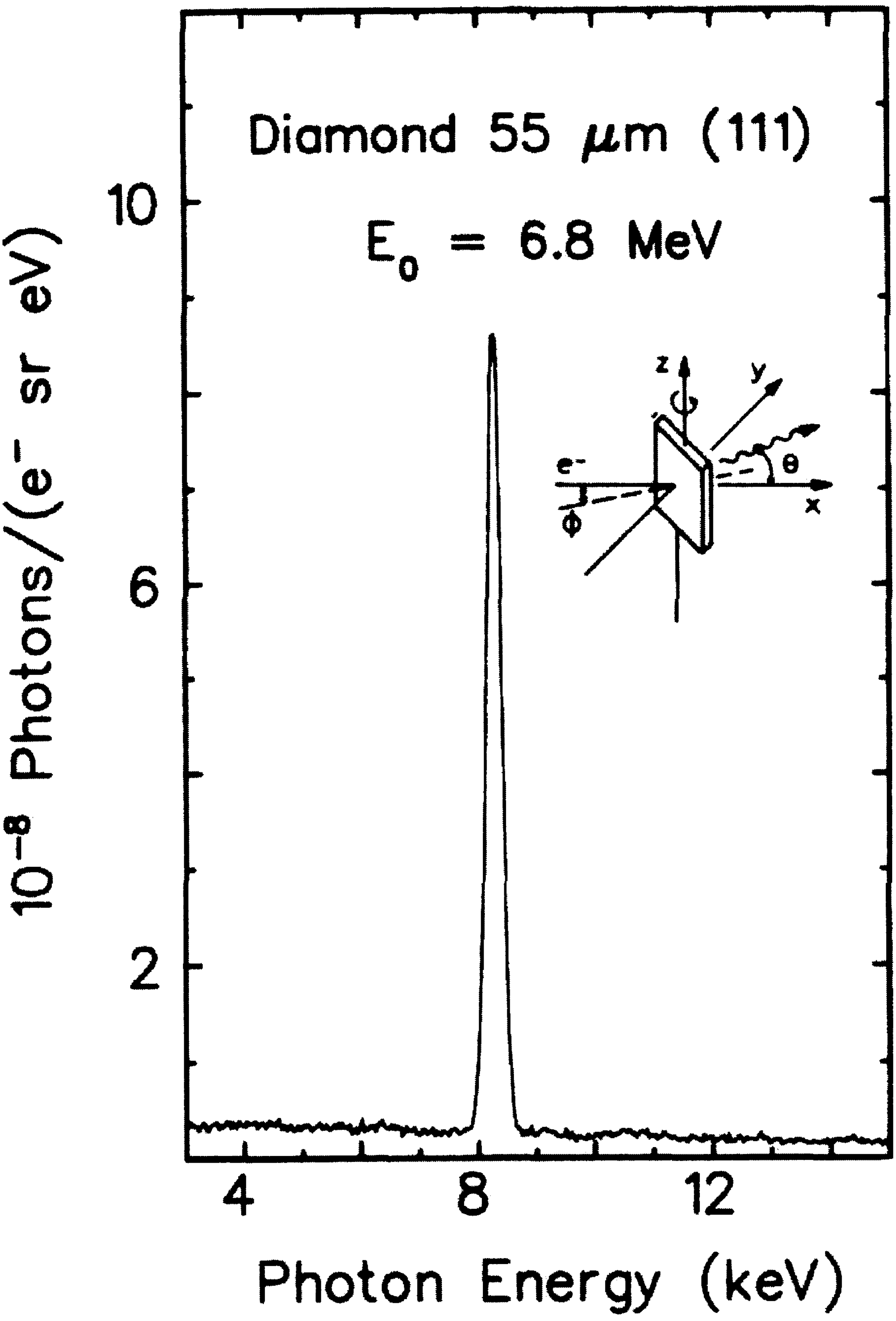
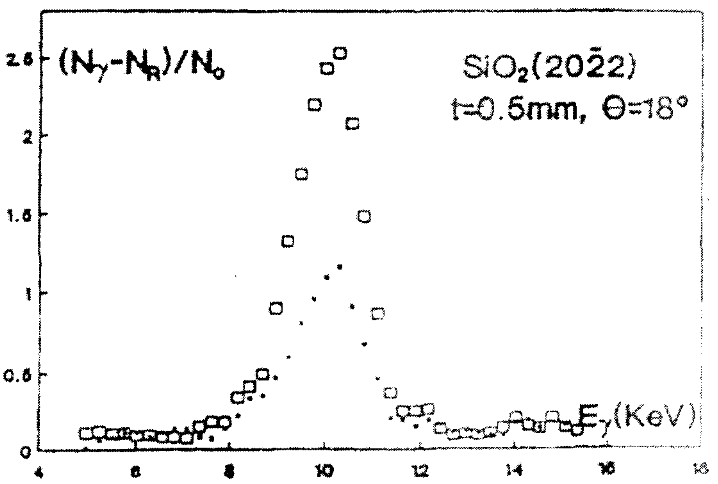

Diamond 55 μm (111)
E0 = 6.8 MeV
z
y
e-
θ
x
Φ
10
6
2
10−8 Photons/(e− sr eV)
4
8
12
Photon Energy (keV)

FIG. 1.



$(N_\gamma - N_R)/N_o$
$SiO_2(20\bar{2}2)$
t=0.5mm, Θ=18°
E_γ(KeV)
2.5
2
1.5
1
0.5
0
4
6
8
10
12
14
16
18

Fig. 2.

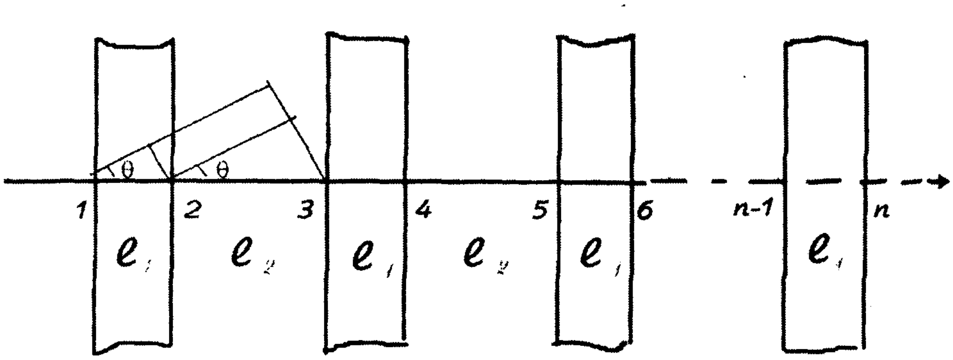
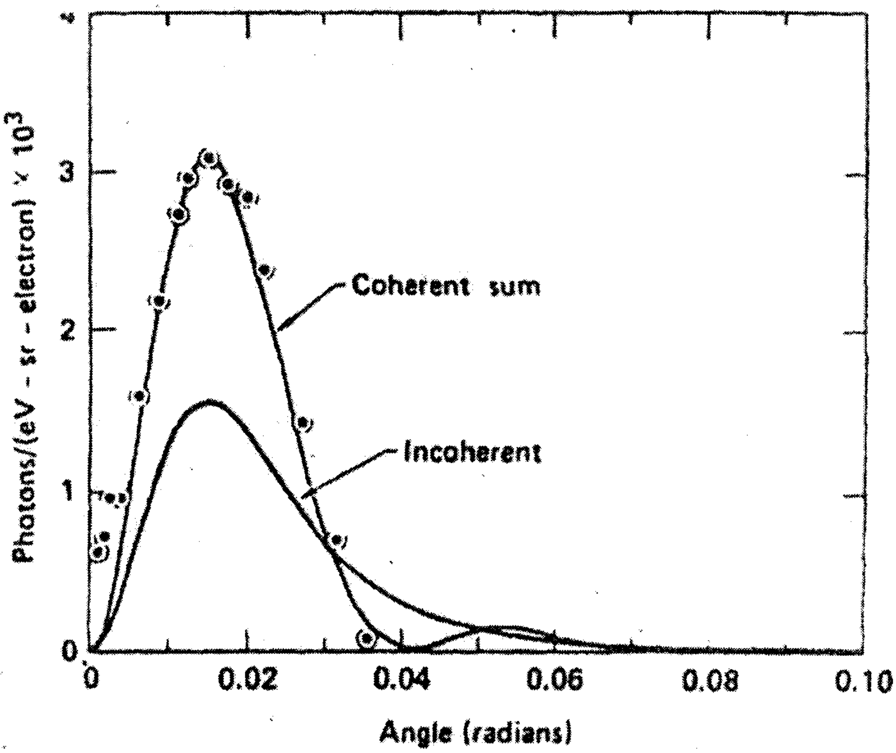
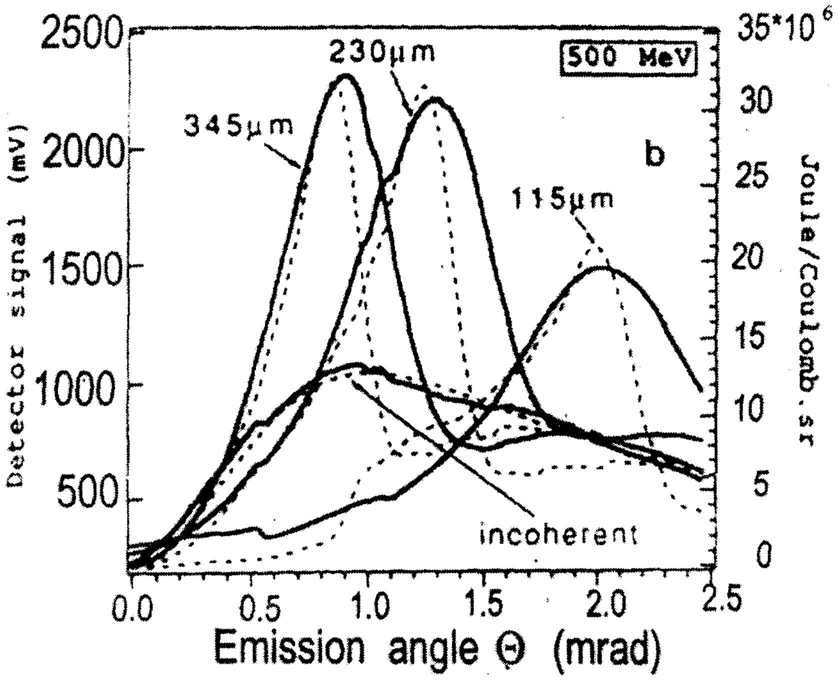


Fig. 3.



Photons/(eV - sr - electron) × 10^3
Coherent sum
Incoherent
0
1
2
3
4
0
0.02
0.04
0.06
0.08
0.10
Angle (radians)

Fig. 4.



2500
2000
1500
1000
500
Detector signal (mV)
35*10^6
30
25
20
15
10
5
0
Joule/Coulomb.sr
500 MeV
b
230μm
345μm
115μm
incoherent
0.0
0.5
1.0
1.5
2.0
2.5
Emission angle Θ (mrad)

Fig. 5.

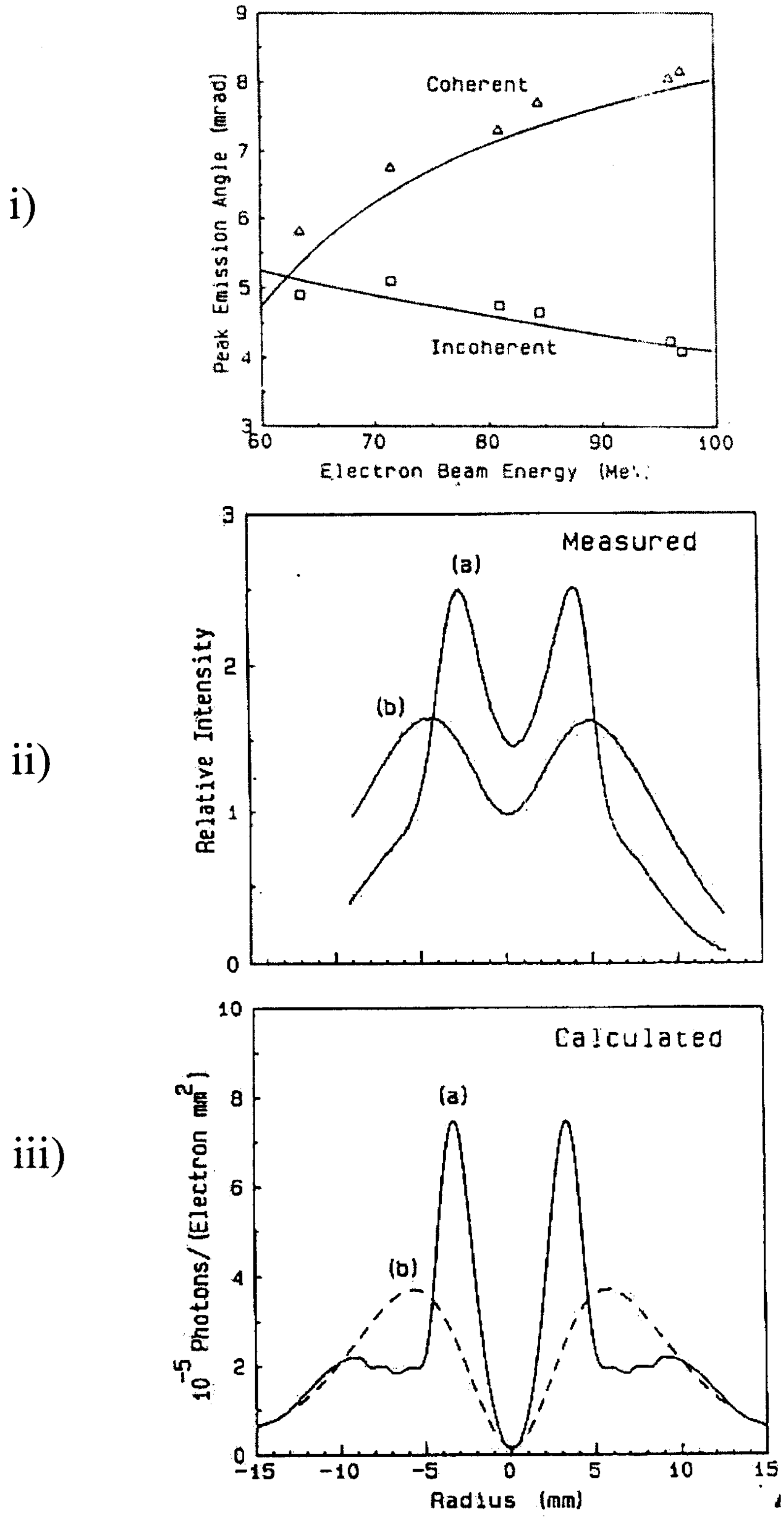
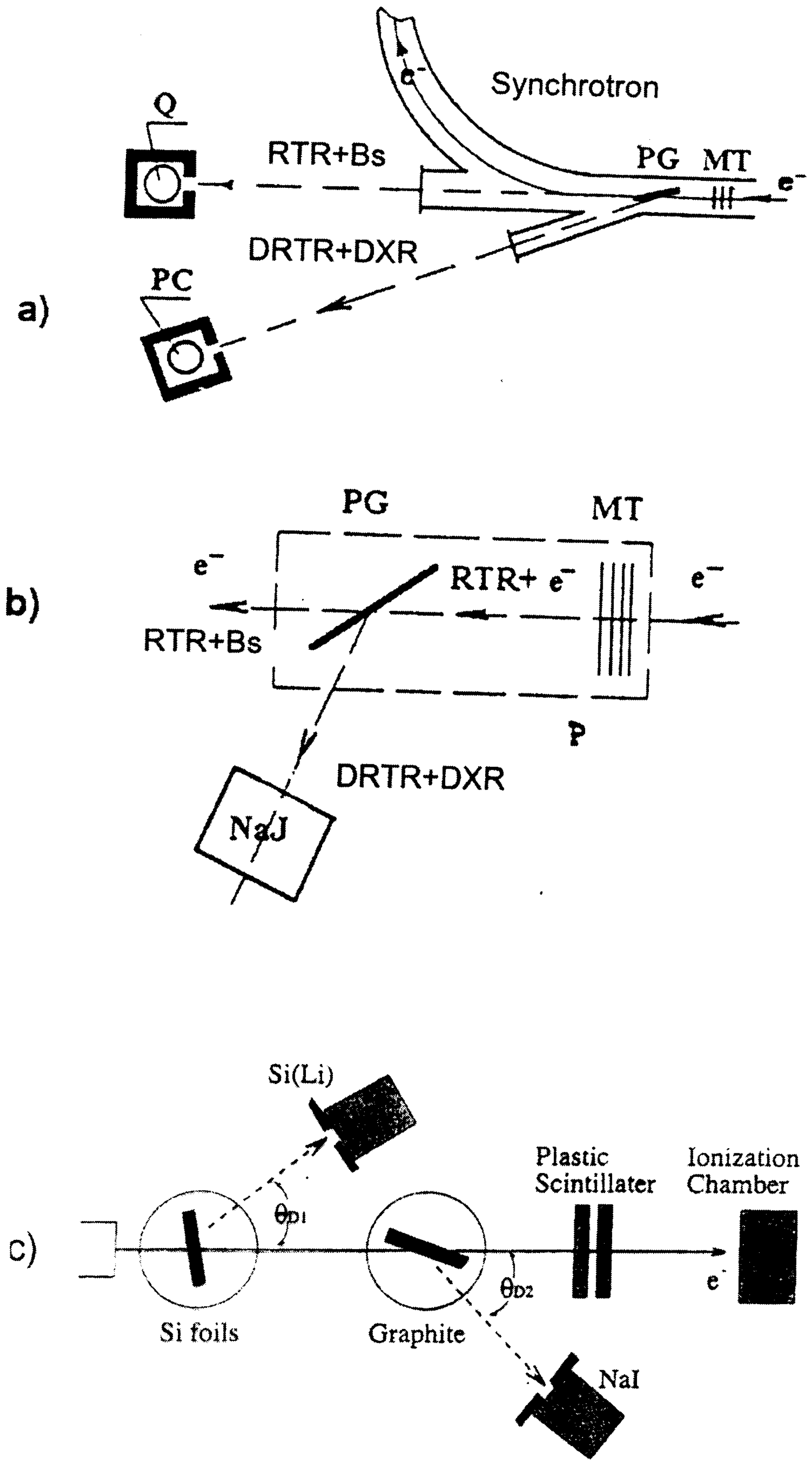

i)
Coherent
Incoherent
Peak Emission Angle (mrad)
Electron Beam Energy (MeV)
ii)
Measured
(a)
(b)
Relative Intensity
iii)
Calculated
(a)
(b)
10^{-5} Photons/(Electron mm^2)
Radius (mm)

Fig. 6.



a)
Synchrotron
e⁻
Q
RTR+Bs
PG
MT
e⁻
DRTR+DXR
PC
b)
PG
MT
e⁻
RTR+ e⁻
e⁻
RTR+Bs
P
DRTR+DXR
NaJ
c)
Si(Li)
θ_{D1}
Plastic Scintillater
Ionization Chamber
Si foils
Graphite
θ_{D2}
e⁻
NaI

Fig. 7.